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# HEAT TRANSFER OF DOWELLED AND BOLTED STEEL-TO-TIMBER CONNECTIONS EXPOSED TO FIRE: EXPERIMENTATION AND NUMERICAL MODELING

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**Abstract**

This exploration is dedicated of the experimental and numerical studies of heat transfer in timber-to-metal connections (bolts and dowels) in a fire exposure. The study was performed experimentally by testing specimens of connections in an oven with gas burner under the action of an ISO 834 fire temperature-time curve. Then, medialization of these specimens is made under the Msc_Marc software. The numerical model is based on finite element modeling. Finally a comparative study and discussions are made between experimental results and numerical ones.

**Keywords:**

Fire, timber, connections, heat transfer, dowel, modelization

## 1 INTRODUCTION

Nowadays, timber structures are well on the way to democratization as regards building uses. They, indeed, present many advantages including light weight, speed of implementation and contribution to sustainable development. These structures are made of timber elements connected together using metal components such as bolts, dowels and nails forming the mechanical joints, which is sometimes reinforced with metal plates. Consequently, the joints are vulnerable areas when exposed to fire. Understanding their mechanical behavior, therefore, is essential, not only as regards fire exposure, but also as regards the coupling of the thermal and hydric fluxes within the connections.

In the past, the development of timber structures has been seriously hindered by wood combustibility, which aroused many questions about fire safety. However, researches have since shown that wood behaves honorably under fire exposure. Wood, indeed, burns slowly and keeps his mechanical properties longer than other materials [EN 1955-1-1 2004], [Buchanan 2000], [Konig 2001]. Its average carbonization rate is about 0.74mm/min whereas carbonized layers form an external protection for the inner parts. Nevertheless, the combination of the architectural demand and the material mechanical resistance requires wood materials to cohabit with other materials like steel fasteners. With the presence of steel members, thermo-hydric heat transfer phenomena within Timber-Steel-Timber ("T-S-T") connections under fire exposure increase in speed and complexity [EN 1993-1-2 2003], [Audebert 2010]. This complexity comes from the difference between the materials regarding mechanical rigidity and thermo-hydric permeability. It affects the mechanical and thermo-physical properties of the materials eventually, in particular, thermal conductivity and specific heat subjected to the thermal action of fire [EN 1995-1-2 2004], [Audebert 2012], [Audebert 2013].

When a T-S-T joint is exposed to fire, each material reacts according to its thermo-physical characteristics. The rate of diffusion of the heat flow is then heterogeneous and depends on the thermal conductivity-temperature evolution of each material (timber and steel). As the temperature increases, with time, in the material, the water contained in timber migrates from areas with a high partial pressure toward some with a lower one and accumulates at the timber/steel interfaces. Heat flux is, therefore, necessarily coupled to a hydric flux, which, when the temperature exceeds 90 °C, initiates a change of phase. Thus, this physical process causes the retardation of the material combustion, the nature and duration of which depend on the moisture content of the timber and the permeability of the materials. A considerable amount of effort has been devoted to the observation of this phenomenon on joints equipped with metal plates: metal plates act as moisture barriers and water is stored at the wood/metal interfaces [EN 1993-1-2 2003], [Audebert 2012], [Audebert 2011]. More recently, combustion slowing down has been represented numerically by a peak on timber specific heat, adjusted from experimental values, when the temperature ranges between 90 °C and 110 °C, (corresponding to the temperature range where water passes from the liquid to the vapor state) [Mischler 1998], [Erchinger 2010], [Cachim 2009].

This article focuses on the study of the comparison of the thermo-hydric behaviour of the doweled connections in two configurations joint Timber-Timber (T-T) and Timber-Steel-Timber (T-S-T) when they are subjected to a thermal load of fire type. For thus, two approaches have been adopted: experimental and numerical modelling. The first concern the thermal testing under fire «ISO 834» type, in a gas oven, on mono-rod Timber-Timber and Timber-Steel-Timber specimens. Finite Element numerical Model 'FEM' has been developed under the MSC.MARC software. This study highlights the effect of the presence of metal plate in the wood connections and its use in the civil construction.

## 2 EXPERIMENTAL STUDIES

### 2.1 Experimental setup

The experimental specimens consist of Timber-to-Timber and Timber-Steel-Timber connections maintained by a single fastener (dowel or bolt). They are commonly used as joints in actual timber structures. The Timber-Steel-Timber specimens include an additional metal plate inserted between both timber members (*Fig. 1* and *Fig. 2*). The timber members are made of class GL24h glulam wood. The measured mean values for moisture content and density are 9.2% and 390 kg/m3, respectively.

*Fig. 1: Test specimen.*

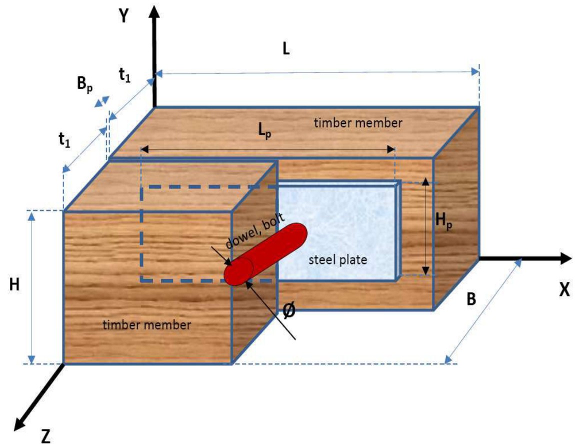



*Fig. 2 : Geometrical dimensions.*

*Tab. 1 : Geometrical configurations*

| N° | Type | L(mm) | B(mm) | H(mm) | $L_p$(mm) | $B_p$(mm) | $H_p$(mm) | $t_1$(mm) | Phi(mm) |
|---|---|---|---|---|---|---|---|---|---|
| S1 | TT | 300 | 155 | 130 | - | - | - | 77.5 | 16 |
| S2 | TMT | 300 | 155 | 130 | 260 | 8 | 64 | 77.5 | 16 |
| S3 | BB | 300 | 210 | 130 | - | - | - | 105 | 20 |
| S4 | TMT | 300 | 210 | 130 | 260 | 10 | 64 | 105 | 20 |

The geometric dimensions are summarized in *Tab. 1*. $S_i$ is the specimen of number 'i'. This geometrical arrangement is chosen to avoid edge effects when the combustion of timber and the connections have been designed according to the technical rules of design [EN 1995-1-1 2004], [EN 1995-1-2 2004]. Three tests are performed with a 16-mm diameter fastener and the three other tests with a 20-mm diameter fastener. For each fastener diameter, three tests are carried out: T-T with a dowel fastener, T-S-T with a dowel fastener and T-S-T with a bolt fastener. All the tests are described in *Tab. 1* below.

The tests are carried out in an 85 x 90 x 70 $cm^3$ gas oven, the inner walls of which are protected by a refractory material. The specimens are placed at mid-height on refractory ceramic blocks. The burner is placed so as to ensure the homogeneous carbonization of the test specimens. The specimens are exposed to fire 30 and 45 minutes at the maximum, respectively.

The thermocouples, withstanding a temperature of 1372 °C, are embedded in different places to record temperatures in both the fastener and the material members (*Fig. 1*, Appendices A1 and A2). The gaps between the members are protected and all the temperature sensors are connected to a computer via a data acquisition system. The temperature of the oven is controlled by adjusting the gas flow so as to follow the "ISO 834" curve (1) evolution (*Fig. 4*). The sampling time step is 0.03 min.

$$\theta(t) - \theta_0 = 345 log_{10}(8t + 1) \quad (1)$$

Where θ(t) is the temperature in the furnace in °C, $\theta_0$, the ambient temperature in °C and t , the duration in minutes.

In order to examine the thermal behavior of the connections, 16 thermocouples are used for each test. Thermocouples TC1, TC2, TC3 and TC4 are used to measure the temperature in the fastener members, TC5, TC6, TC7 and TC8 in the material, TC9, TC10, TC11 and TC12 in the timber-metal interface and the four other thermocouples (*Fig. 1*) are placed in the oven around the specimen to control the temperature of the gas near the outer walls (Appendices A1 and A2).

### 2.2 Carbonization-charring rate

The carbonization results confirm the homogeneous charring of all the exposed sides of the specimen (Fig. 3). The combustion rate is assessed by measuring the residual sections. Thus obtain an average burning speed of 0.71 mm/min (Tab. **2**), which is close to the value recommended by the [EN 1995-1-2 2004] Eurocode standard (0.70 mm/min).

*Tab. 2 : Charring rate*

| N° | t (min) | $\beta_{n,lat,l}$ | $\beta_{n,lat,r}$ | $\beta_{n,h,t}$ | $\beta_{n,h,b}$ |
|---|---|---|---|---|---|
| S1 | 37 | 0,71 | 0,70 | 0,67 | 0,69 |
| S2 | 40 | 0,73 | 0,76 | 0,67 | 0,62 |
| S3 | 30 | 0,76 | 0,77 | 0,71 | 0,74 |
| S4 | 30 | 0,75 | 0,74 | 0,71 | 0,79 |
| $\beta_{n,mean}$ | | | **0,71** | | |

*Fig. 3 : Carbonization of timber members.*

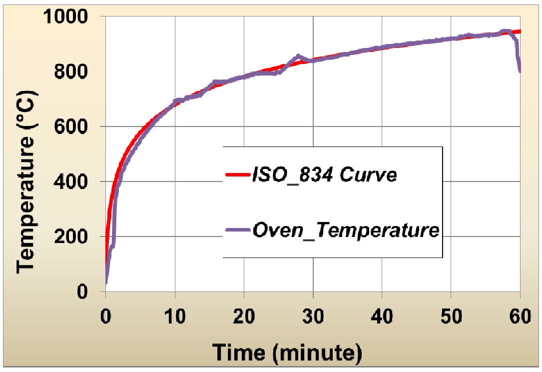



*Fig. 4 : ISO 834 temperature-time evolution*

Tab. 2 summarizes the different burning speed values for the four sides of the specimen. The $\beta_{n,mean}$ factor is the average combustion rate (mm/min), $\beta_{n,lat,l}$ and $\beta_{n,lat,r}$ are the burning speeds for the left and the right walls, respectively, and $\beta_{n,h,t}$ , $\beta_{n,h,b}$ are those for the top and bottom walls, respectively.

### 2.3 Heating of timber near the fastener members

Around the hole of the steel fasteners, heat transfer effects between member and metal fasteners are clearly shown (*Fig. 5*). This influence can be substantial when the joints are mechanically stressed during fire exposure, because it generates weak breaking points and slotting within the hole.

The temperatures measured with thermocouples TC1, TC2, TC3 and TC4 placed near the metal rod are presented in *Fig.* , where “d” and “b”, hereafter, stand for Dowel or Bolt, “TCn-dxx” is the thermocouple number “n”, “xx” the diameter in mm (16 or 20).

The temperature curves of the doweled joint (*Fig.* ) perfectly agree with reality. TC2 and TC3 are protected by wood whereas the temperatures of TC4 and TC1 are higher than TC2 in both test configurations (for Ø16 and Ø20 rods). Such differences, obtained with the same thermocouple, can be accounted for by the difference in thickness “B” (Appendices A1 and A2). Temperatures near metal are measured with thermocouples TC9, TC 10, TC 11, and TC12 (Appendices A1 and A2).

*Fig. 5 : Heating of dowel and metal plate.*

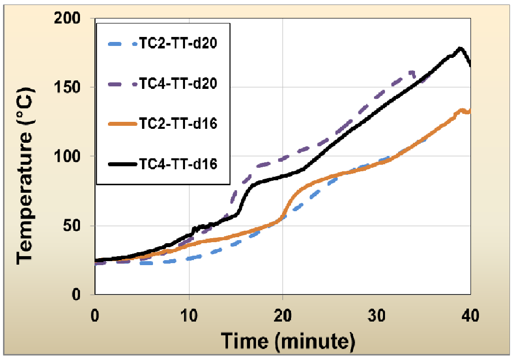



*Fig. 6 : Timber near fasteners*

Fig. 7 illustrates wood temperatures-time evolution in the interface timber-metal plate. Temperatures measured inside the TMT connections are represented by the red curve and the blue curve is about TT connections.

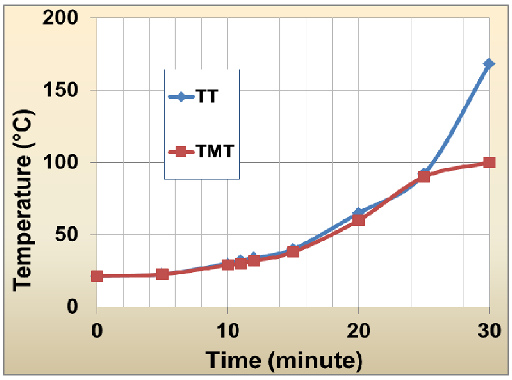



*Fig. 7 : Interface timber-metal plate*

We observe that both curves are close when the temperatures are under 90°C. Beyond these values, the blue curve got a normal temperature-time evolution while the red curve presents a slowdown. It takes about 5 to 7 minutes in the case of the TMT dowelled to reach the same temperatures (TT). This slowdown is due to the phase change within timber members when temperature is around 100°C and at the presence of the metal plate. The water within the wood goes toward inside the joints, then stagnates against the metal plate during the warming up of the timber members and produces an endothermic chemical reaction. This leads to the slowdown observed.

## 3 FINITE ELEMENT METHOD (FEM) MODELING

Finite element modeling is carried out using the Msc-Marc piece of software. Each solid is modeled separately with 20-node hexahedral solid elements (*Fig. 8* and *Fig. 9*). Then, the whole joint is assembled by defining contact points between the solids. To ensure the continuation of the thermal field, the mesh is finer in the contact areas between solids. In view of symmetry, only half of the joint is modeled. The global mesh, however, is continuous.

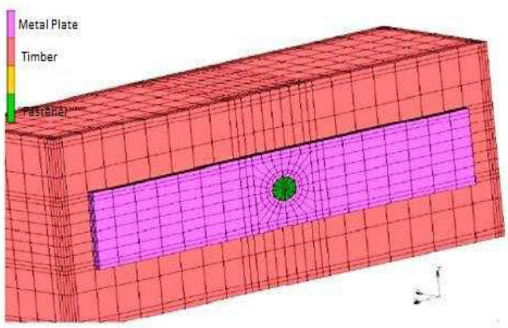



*Fig. 8 : FEM modeling.*

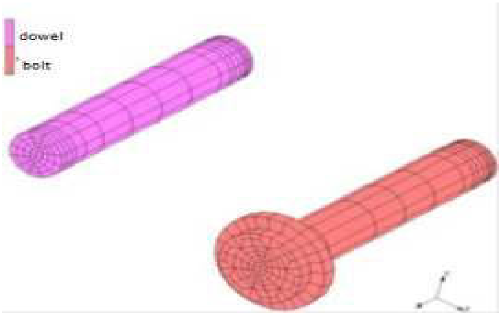
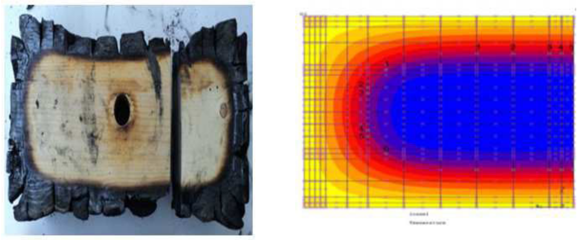



*Fig. 9 : FEM modeling of bolt and dowel.*

The peak value of Cp, Cp=10 ( kJ/kg/K ), is necessary in the case of T-S-T joints so as to consider the phase change of the water stored at the interfaces of the metal plate when the local temperatures are within the range 90-110 °C.

The global finite element calculation is in good agreement with the experimental observations as regards the carbonization rate as shown in Figure 10. The calculated temperatures of the charred parts are similar to the experimental values, i.e., close to the 300°C isotherm. The numerical char thickness, $d_{char}$, obtained is homogeneous on the external walls in contact with fire because an identical value for both the thermal conductivity and the specific heat is chosen for all the geometrical axes of the timber elements. However, the value charring-rate MEF=0.90mm/min is satisfactory compared with the experimental values, charring rate EXP=0.70mm/min and charring rate Eurocode5=0.71mm/min. The relative difference between numerical and experimental values is about 29%.



(A) (B)

*Fig. 10 : experimental and numerical carbonization.*

*Tab. 3* presents numerical results of temperatures for different tests duration (t=10min, t=20min and t=30min). Then, we make a comparison between these values and experimental values.

Globally, the numerical results are satisfactory in comparison to experimental results. The relative error between both results are remains lower than 35% for all the tested connections. This can be explained by the combination of highly variable material thermos-physical characteristics and the consideration of heat and hydric fluxes in the joints and makes numerical modeling complex.

*Tab. 3 : Comparison between experimental and FEM*

| parts | TC | EXP/NUM | t=10 min | | t=20 min | | t=30 min | |
|---|---|---|---|---|---|---|---|---|
| | | | TT | TMT | TT | TMT | TT | TMT |
| Near fastener | TC1 (TC4) | EXP | 38 | 30,7 | 87,6 | 66 | 141 | 197,7 |
| | | NUM | 26,8 | 30,7 | 58,7 | 77,8 | 104,8 | 157 |
| | | Diff (%) | 29% | 0% | 33% | 18% | 26% | 21% |
| interface metal-pate | TC6(TC7) | EXP | 28,9 | 29,5 | 34 | 33,6 | 77,3 | 79,8 |
| | | NUM | 26 | 29 | 26,7 | 47,5 | 53 | 95 |
| | | Diff (%) | 10% | 2% | 21% | 41% | 31% | 19% |

## 4 CONLUSION

This work consisted to make comparison between timber-to-timber connections and timber-metal-timber connections thermo-hydric behaviour. These tests show that timber-metal-timber connections present a temporal slowdown (about 6min) when temperatures are around 100°C. A finite element method model is proposed for the connections study. The obtained results are in good agreement with the real ones. Firstly this study allows us to reduce the number of experimentation of the connections when exposed to fire and thus, to save money. Secondly it goes in the direction to promote the use of timber in the civil construction.

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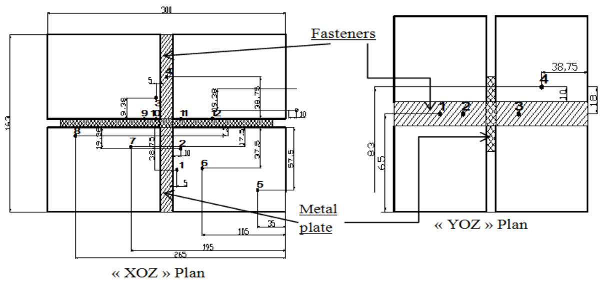
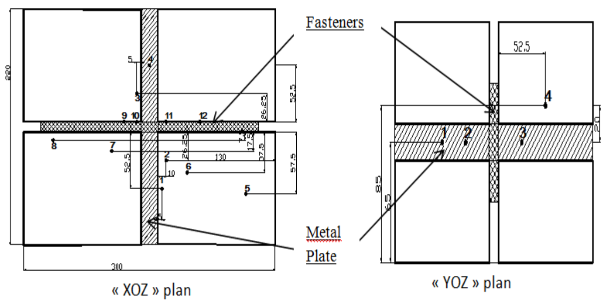
## 6 APPENDICES




A1




A2